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A Critical Review of “Travelling Fire” Scenarios for Performance-Based Structural Engineering

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ABSTRACT

Many studies of the thermal and structural behaviour for large compartments in fire carried out over the past two decades show that fires in such compartments have a great deal of non-uniformity (e.g. Stern-Gottfried et al. [1]), unlike the homogeneous compartment temperature assumption in the current fire safety engineering practice. Furthermore, some large compartment fires may burn locally and tend to move across entire floor plates over a period of time. This kind of fire scenario is beginning to be idealized as *travelling fires* in the context of performance-based structural and fire safety engineering.

This paper presents a literature review of the travelling fire research topic and its state of the art, including both the experimental and theoretical work for the past twenty years. It is found that the main obstacle of developing the travelling fire knowledge is the lack of understanding of the physical mechanisms behind this kind of fire scenario, which requires more reasonable large scale travelling fire experiments to be set up and carried out. The demonstration of the development of a new travelling fire framework is also presented in this paper, to show how current available experimental data hinder the analytical model development, and the urgent need that the new travelling fire experiments should be conducted.

KEYWORDS: structural fire design, travelling fires, compartment fires, performance-based design.

INTRODUCTION

The “travelling fire” methodology originating at the University of Edinburgh in 2007, due to Rein et al. [2], postulates that fires may burn locally and move across the entire floor plate over a period of time in large compartments. It was proposed on the basis of observed fire dynamics from real fires and a few experimental programmes that have occurred over the past two decades, such as [3]–[6].

In real life, travelling fires have been observed in several structural failures especially since 2000: the World Trade Center Towers [7] in New York City in 2001, the Windsor Tower [8] in Madrid in 2005, and the Faculty of TU Delft Architecture building [9] in Netherlands in 2008. Looking closely at an example of an open-plan modern building, i.e. the Informatics Forum that opened at the University of Edinburgh in 2009, a statistical survey indicated that traditional fire safety design methods were applicable to only 8% of the total volume of the building (other areas being out-of-range by Eurocode limitations, e.g. opening factor (>0.2), compartment height ($>4\text{m}$), size of the compartment ($>500\text{m}^2$) [10]). These facts underline the need for a better description of fire scenarios that recognise the radically different spatial layouts preferred in contemporary architecture. There is currently greatly increased interest in methodologies for representation of more realistic fire scenarios for the purposes of fire safety engineering design.

In 2012, a review paper was published by Stern-Gottfried & Rein [11]. It summarized several fire tests conducted in the large compartments (e.g. [3]–[5]) as experimental evidence which clearly showed the temperature heterogeneity in such compartments. There have been three further large scale travelling fire tests performed from 2011 to 2015. In 2011, to investigate how the travelling fires impact the steel structural components especially for beam-to-column connections, a full-scale travelling fire test was conducted at the upper floor of a two-storey steel composite building in Veselí, in the Czech Republic [12]. In 2013 a series of experiments were conducted at the Building Research Establishment (BRE) in UK as part of the EPSRC funded research project ‘Real Fires for Safety Design of Tall Buildings’ [13]. The project intended to obtain a better understanding how a fire progresses in a large compartment and affects the temperature distribution spatially and temporally. In 2015, another experiment called the Tisova Fire Test [14] was conducted in the Czech Republic inside a 4-storey concrete frame building, in order to test the travelling fire methodology put forward by Stern-Gottfried & Rein [15].

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Moreover, two main theoretical representations of travelling fire models can be found in the current literature, hereinafter referred to as: Clifton's model [16]; and Rein's model [11], [15]. Clifton developed a fire model, which divides the whole large compartment into several design areas, which are then subjected to time-temperature curves individually and sequentially. In Rein's model, Alpert's correlation is adopted to calculate far field smoke temperature, and a uniform temperature (800°C – 1200°C) is assumed for the near field. However, both models necessarily neglect some aspects of the fire dynamics. For instance, the accumulation of a hot smoke layer is ignored in both models. In Clifton's model, all elements in one 'firecell' (one design area) share the same fire exposure history. In Rein's model the uniform 800°C-1200°C assumption is very generic. In 2016, a new travelling fire framework was proposed by Dai et al. [17], [18]. It is based on a "mobile" version of Hasemi's localized fire model, combined with a simple smoke layer calculation for the areas of the compartment away from the fire. This combined fire model enables the analysis to capture both spatial and temporal changes of the thermal field which is then automatically coupled to a thermomechanical analysis using the software framework OpenSees [19].

This paper is divided into three sections: firstly, several large-scale fire experiments are reviewed, especially the ones labelled as travelling fire tests; secondly, a literature review of the current analytical travelling fire models is summarized, including the recent travelling fire framework proposed by the authors (Dai et al. [17], [18]); thirdly, a demonstration of the newly developed travelling fire framework is also presented, to show how existing experimental data hinder the analytical model development highlighting the urgent need for new travelling fire scenario experiments.

EXPERIMENTS CONDUCTED FOR CHARACTERISING TRAVELLING FIRES

This section reviews the experiments that fires in which a 'travelling' nature in large compartments, with a particular emphasis on the ones labelled as *travelling fire tests* conducted for the past five years.

Fire Tests of a 'Travelling' Nature Before 2010

Although true dynamics of travelling fires has received "zero attention" in large scale structural fire tests [20] (as summarized by Bisby et al. in 2013), there are still some experiments where a 'travelling' nature of the fire is recorded in the literature.

In 1993, to validate the 'Time Equivalent' formula given in Eurocode 1 for buildings with large compartments, a series of nine tests were carried out at BRE Cardington laboratory [3]. The dimensions of the test compartment were 22.8m long \times 5.6m wide \times 2.75m high (128m² floor area) with uniform wood cribs as the fuel load, and the ventilation was at one end of the long compartment. The fuel was ignited at the opposite end to the ventilation (apart from Test 9, which was ignited simultaneously for comparison), and it was observed that the fire spread quickly to the ventilation side, consumed all the fuel near the vent region, and then the fire travelled back to the ignition region and burned out. Both the gas temperatures and steel temperatures of the protected and unprotected steel members were recorded for the entire duration. Cooke [21] took additional measurements including thermal radiation, gas analysis, air flow, and crib weight loss in the experiment.

In 1995-1996, an experimental testing programme took place on an eight storey steel-framed structure, at BRE Cardington Large Building Test Facility (LBTF). This research programme contains four tests, in which the fourth one - Demonstration Furniture Test - was to investigate the impact of a more realistic fire scenario to the whole structure [22]. The test compartment was 18m wide and up to 10m deep (135m² floor area), to represent an open plan office with modern day furnishings, computers and filing systems, which are equivalent to the fuel load density of 45.6kg of wood/m². Both the ignition method and the ventilation conditions were designed to assist the fire growth, which generated non-uniform (migrating) fire scenarios during the test [23]. The gas temperatures, beam and column temperatures, and the connection temperatures were all measured. Moreover, the structural response was also recorded, including the strain along the columns, the deflections of the beams and floor slabs. All these test data can be found at the One Stop Shop web site, which is maintained by the University of Manchester [24].

In 1999-2000, a series of eight large compartment fire tests were undertaken at BRE Cardington LBTF, to validate the zone models as part of the Natural Fire Safety Concept (NFSC) framework. These eight tests were full-scale post-flashover fires conducted in a large compartment with approximate dimensions 12m \times 12m \times 3m high (144m² floor area), with different opening situations, fire load compositions (wood cribs only, or 80% wood cribs + 20% plastic), and the compartment boundary linings [25]. Thermocouples were

distributed throughout the compartment for recording gas temperatures, and the steel temperatures were measured for both the structural components with and without protections. Mass loss was also recorded through the tests by using load cells. The spatial and temporal change of the heat flux fields under the ceiling were produced by Welch et al. in Fig. 1 [6]. The maximum recorded temperature was over 1330°C .

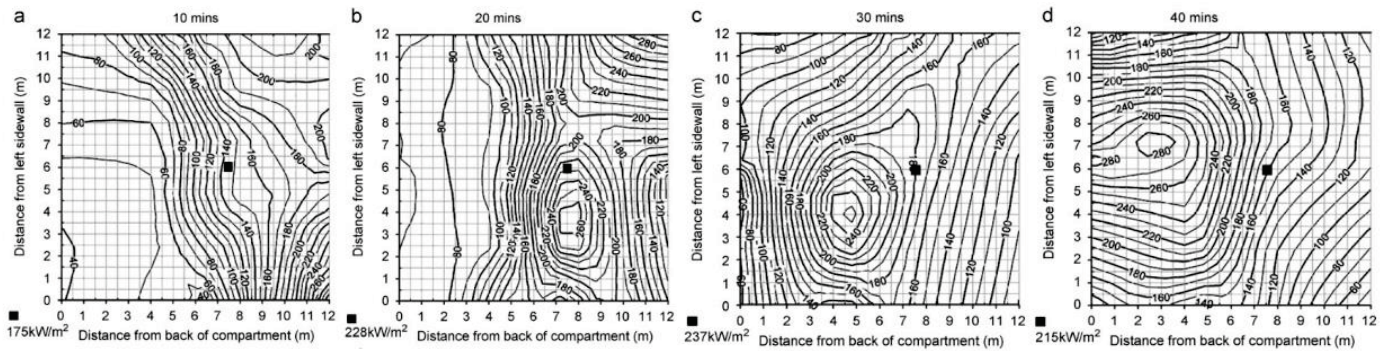


Fig. 1. Heat flux map under the compartment ceiling, reprinted from Welch et al. [6] with permission from Elsevier.

In 2005, a series of eight experiments were conducted by Thomas et al. [26] for investigating the fire behaviour in a deep enclosure with various openings in one end. The steel enclosure for the tests has dimensions of 8.0m long \times 2.0m wide \times 0.6m high (16m^2 in area), with sixteen steel fuel trays containing 97% ethanol (see Fig. 2(a)). Only the front end of the enclosure was ventilated with different opening sizes for the eight tests. Both gas temperatures and steel temperatures were recorded during the test (maximum thermocouple temperature was around 850°C) (see Fig. 2(b)), and a calorimeter hood was used for collecting the outgoing combustion products to estimate the heat release rate. A load cell was placed beneath each tray to record the mass loss of the fuel throughout the test.

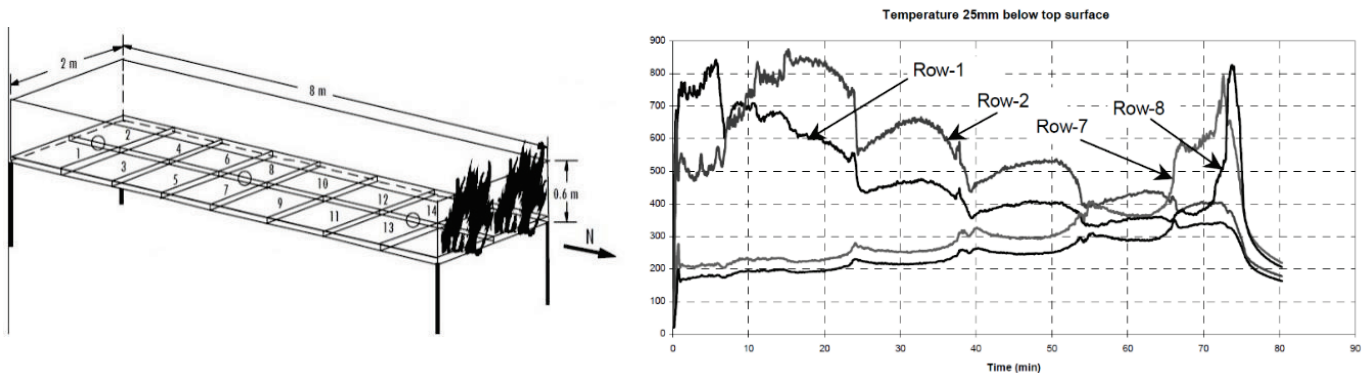


Fig. 2(a). Schematic diagram of experimental test configuration; and Fig. 2(b). Gas time-temperature curves above the front and back rows, Thomas et al. [26]. (Fig. 2(a) is reorganised for saving space)

In three of the four sets of tests mentioned above: Kirby [3] & Cooke [21] in 1993, NFSC - BRE Cardington [6][25] in 1999-2000, and Thomas et al. [26] in 2005, all showed similar ventilation controlled fire dynamics in large compartments. In all three cases, the fire was ignited away from the ventilation area, rapidly spreading towards the area of abundant oxygen near the vent, exhausting the fuel near the vent, and then slowly burning back away from the vent area, consuming the majority of the available fuel.

Although more fire tests with a ‘travelling’ nature can be found in the literature, such as the St. Lawrence Burns project reviewed by Gales [27], due to the page limit, the emphasis of this paper is about the state of the art of the travelling fires, hence only typical ‘spreading’ fire tests are reviewed as above. The following subsections present three large scale experiments labelled as *travelling fire tests*.

Veselí Travelling Fire Test (Czech Republic, 2011)

This test was part of an European-funded project called COMPFIRE [28], investigating the behaviour and robustness of the practical beam-to-column connections under travelling fire scenarios. The experimental building was a $10.4\text{m} \times 13.4\text{m}$ in plane \times 9m in height (139m^2 floor area) two-storey steel composite structure, with a $2\text{m} \times 5\text{m}$ unglazed opening for each floor to provide enough ventilation for a smooth development of the fire (see Fig. 3(a)). The height of each floor was 4m . The fuel load was wood cribs dried

to moisture content of 12%, with density 173.5 MJ/m^2 , distributed on the second floor, with a $3\text{m} \times 8\text{m}$ rectangular shape as shown in Fig. 3(b), with the desired fire path parallel to the ventilation opening rather than perpendicular to it. In addition, no mechanical load was applied during the entire travelling fire test.

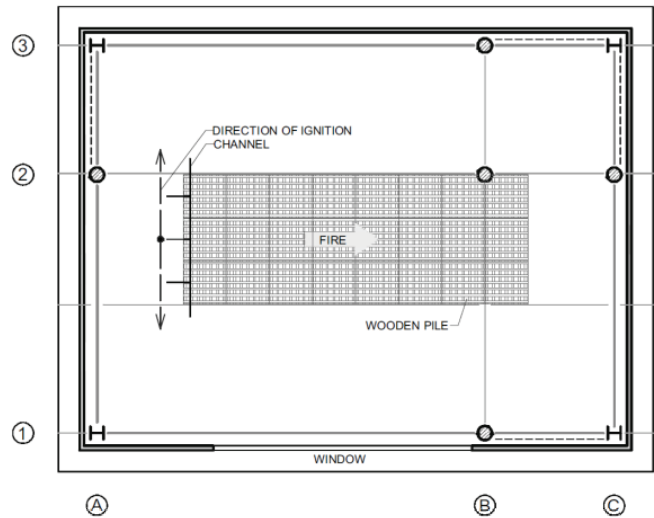


Fig. 3(a). Experimental building during Travelling fire test (photo provided by Horová K., CVUT in Prague); and Fig. 3(b). Fuel load scheme, in hatched, on the upper floor of the experimental building, Wald et al. [30].

Fig. 4 shows the fire development with a time step of every 5 min during the 40 min test duration. The fire was first ignited with a linear source on the left-hand side, then the flame spread gradually to the right, accompanied by a smoke layer generation beneath the ceiling for the beginning 15 minutes. Then more fuel was on fire with a maximum gas temperature recorded of 979°C at 26 min. From 30-40 min, the process of the fire burn out can be clearly seen. Furthermore, neither flashover nor structural failure was observed during the test [28][29].

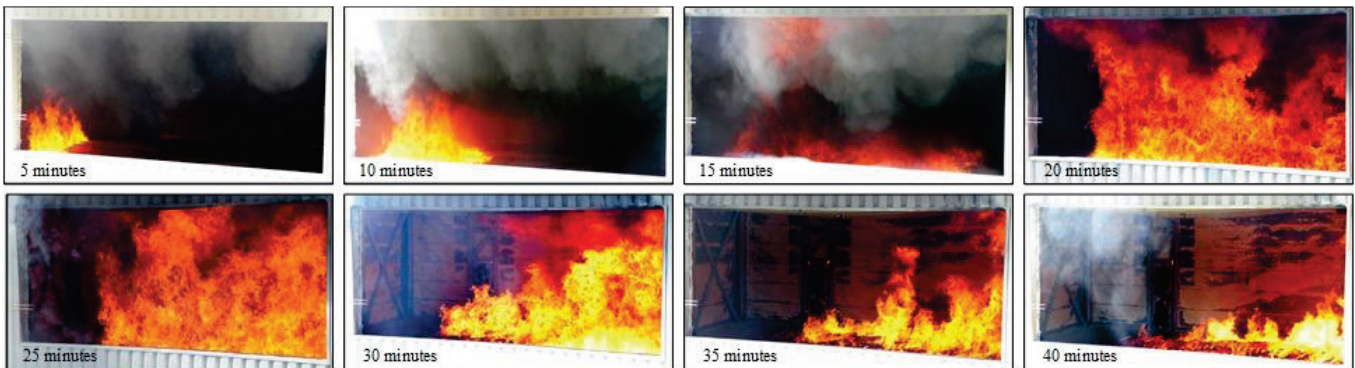


Fig. 4. Development of the fire during the test (photos provided by Horová K., CVUT in Prague).

Importantly the temperatures of the gas atmosphere, steel beam at mid-span, connections, composite slabs, and columns were all measured. Unlike many similar tests, the structural response was also extensively recorded, including the vertical and horizontal displacement of the slab, the deflection of the beam mid-span, and the strain gauge on the columns for estimating the forces of the connections [30].

BRE Travelling Fire Test (UK, 2013)

In 2013 a series of experiments in support of the project ‘Real Fires for Safe Design of Tall Buildings’ [13][43] was conducted by the University of Edinburgh at the BRE in UK. The aim of these experiments is for obtaining a better understanding of how a fire progresses in a large compartment and affects the temperature distribution spatially and temporally.

The experimental compartment was $5\text{m} \times 18\text{m}$ in plane $\times 2\text{m}$ in height (90m^2 in area), with 15 potential openings (1.5m high $\times 1\text{m}$ wide) along the front of the compartment. These openings were adjusted in the course of the tests to allow different ventilation progressions; one series of tests adopted sequentially ignited gas burners with different fire spread rate and ventilation combinations, and the other, wood cribs, these

being ignited at one end of the compartment to allow the fire to propagate parallel to the openings. Load cells were used to measure the crib mass loss.

An example of the fire development in the experimental compartment can be seen in Fig. 5, which presents the temperature distributions of the plane parallel to the compartment openings in the wood crib fire test [13]. During this test, the ventilations were fully open to allow the maximum of smoke to evacuate. The fire was ignited at the right hand corner of the long compartment, and it spread very slowly compared to the propagation of the smoke under the ceiling (Fig. 5(a) to (d)). At about 1500 seconds (Fig. 5(e)), the temperature of the smoke exceeded 500°C , and a localized flashover was observed in the right half of the compartment (Fig. 5(f)). Then the flame continued to spread to the left hand side of the compartment, however no further flashover was observed due to the evacuation of the smoke and strong air entrainment from left side to the right side (Fig. 5(g)).

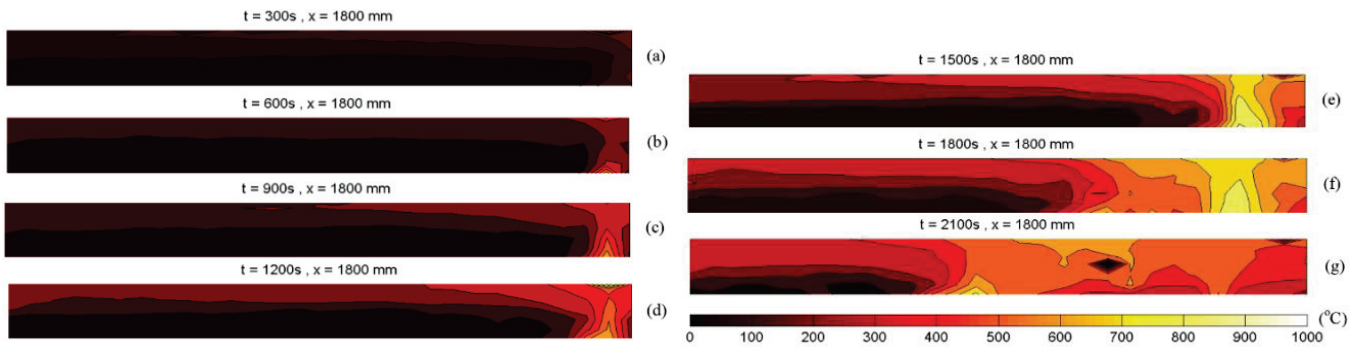


Fig. 5. Temperature distributions along the plane of the openings, Torero et al. [13].

Tisová Travelling Fire Test (Czech Republic, 2015)

This is the latest travelling fire test reported in the literature [14], [31]. It was conducted by a team from SP, the University of Edinburgh, Imperial College London, Luleå Technical University, Technical University Ostrava, Majaczech, CSTB and CERIB, to investigate travelling fires and their impact on concrete and composite structures. The Tisová fire test structure was a four-storey concrete frame centred around a lift shaft, with the travelling fire test compartment located on the ground floor with a total area of 230m^2 in plane $\times 4.4\text{m}$ in height (see Fig. 6). The large test compartment was well ventilated to fit in with the idealization made by Rein in his travelling fire model, which assumes that the travelling fire is entirely fuel controlled, i.e. ventilation is not limiting [15]. The fuel load was wood cribs uniformly distributed on the whole floor with a density of approximately 680 MJ/m^2 .

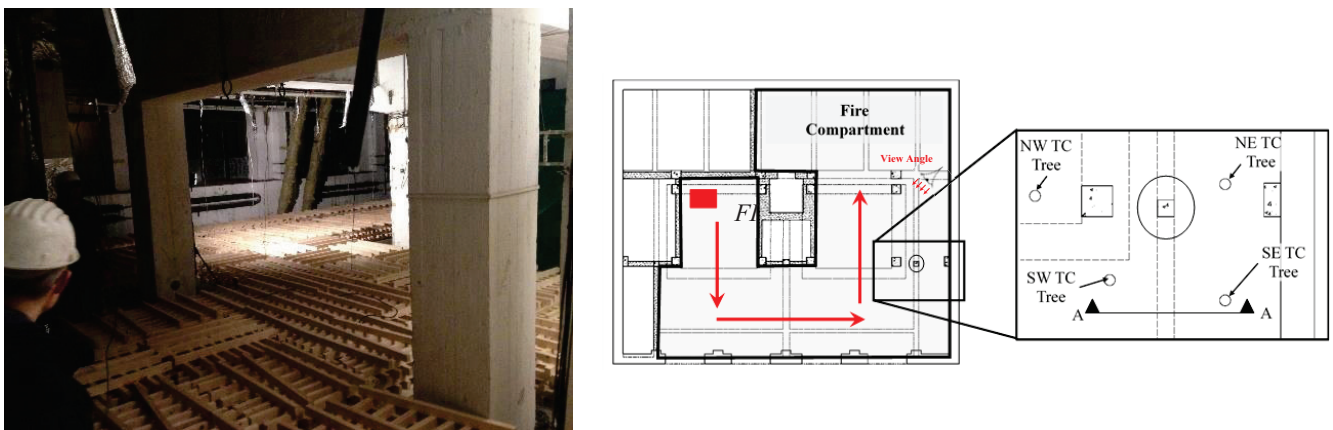


Fig. 6(a). View inside of the experimental compartment (photo provided by Rush D., Tisova Fire Test-2015, report forthcoming); and Fig. 6(b). Fire path and instrumented column, reprinted from Rush et al. [31], with permission from DESTech Publications, Inc. (The view angle of Fig. 6(a) is shown in Fig. 6(b).)

Fig. 6(b) shows the fire ignition (FI) point, fire path, and the instrumented column C1 ($30\text{cm} \times 30\text{cm}$) in the fire compartment. Once the fire was ignited, it spread very slowly and the measured temperature near the ceiling was below 100°C . This was apparently not as challenging a fire to the structure as intended. Therefore, the team decided to reduce the ventilation and add 10 litres of hydrocarbon accelerant to the wood

cribs at time 2.5 h. This produced a more severe fire, however when the fire proceeded to the north of the compartment, the spread rate slowed down again. It was concluded that the poor severity of the fire was mainly because of the high moisture content of the wood cribs, i.e. 18-22%, rather than the targeted 11% [31].

In this travelling fire test, gas temperature, the concrete column temperature, and the slab deflections were measured. Of particular note, it was found that the smoke preheated the top of the column C1, which was located far away from the fire ignition point. When the fire had travelled to the vicinity of the column, it was found that the lower part of the compartment experienced higher temperatures than near the ceiling. It was also shown that the equivalent time method under the ISO-834 fire curve is not appropriate for predicting the temperature of the columns under the travelling fire scenarios, which implies that a new design method for columns in large compartment under fire may be needed in the future [31]. Analysis of the thermal and structural response of these tests is still ongoing at the University of Edinburgh and SP.

Summary of the Experiments

In general, these experimental reviews are focused on tests which have used ‘spreading’ fires, with a particular emphasis on the latest three large scale travelling fire experiments. The reviews aim at obtaining a better understanding of the travelling fire research frontier, and providing recommendations for future experimental research needs on this topic. Table 1 summaries the tests reviewed in the previous subsections. It is categorized with respect to the scale of the experiment, the fuel load type, the measurement of the thermal response, structural response (strain, deflections, etc.), and the mass loss of the fuel.

Table 1. Summaries of the experiments reviewed for travelling fires.

Categories Experiments	Dimensions	Fuel load	Thermal response	Structural response	Mass loss measurement
Kirby [3] & Cooke [21], 1993	22.8m × 5.6m × 2.75m	Wood cribs	Gas and steel temperatures	None	Yes
LBTF – Denmonstration Furniture [22] [23] [24], 1995-1996	135m ²	Furniture	Gas and steel temperatures	Strain and deflections	No
NFSC - BRE Cardington [6] [25], 1999-2000	12m × 12m × 3m	Wood cribs only, or 80% wood cribs + 20% plastic	Gas and steel temperatures	None	Yes
Thomas et al. [26], 2005	8.m × 2.m × 0.6m	Commercial grade methylated spirits (97% ethanol)	Gas and steel temperatures	None	Yes
St. Lawrence Burns project [27], 1958	11.2m × 12.8m, and 13m × 9m	Wood waste	Gas temperatures	None	No
Veseli Travelling Fire Test [12] [28] [29] [30], 2011	10.4m × 13.4m × 4m	Wood cribs	Gas, steel, and concrete temperatures	Strain and deflections	No
BRE Travelling Fire Test [13] [43], 2013	5m × 18m × 2m	Gas burners, or wood cribs	N/A	N/A	Yes
Tisová Travelling Fire Test [14] [31], 2015	230m ² × 4.4m	Wood cribs + hydrocarbon accelerant	Gas and concrete temperatures	Deflections	No

It is obvious in Table 1 that most experimental floor areas were larger than 100m², and wood cribs were commonly used as the fuel load. Gas and structural member temperatures were typically recorded for most cases. Of special interest is a finding that the test in which structural response was recorded did not record the mass loss rate of the fuel, and vice versa. It suggests that the researchers who conducted the measurement of the structural response (probably structural engineers), had less interest in the fire dynamics, as the mass loss of the fuel is a key factor to estimate heat release rate (HRR). Conversely, the researchers who conducted the measurement of the mass loss (probably fire engineers), took less interest in the fire impact induced structural response. This finding confirms a viewpoint expressed by Buchanan in 2008 [32], that “fire engineers and structural engineers need to talk to each other much more than they do now, and each group needs to learn as much as possible of the other discipline.” This argument becomes more essential for the advancement of the topic of travelling fire research, as all the current analytical travelling fires models were

developed for structural fire design, and based on simple fire dynamic assumptions and experimental observations. The details of these analytical models are reviewed below.

ANALYTICAL MODELS FOR TRAVELLING FIRES

Whilst there is still a large amount of uncertainty regarding the fire dynamics within large compartments, there have been calls to bring the travelling fire concept into structural design. Commencing about twenty years ago different theoretical modelling approaches have been developed: Clifton's model [16], Rein's model [11], [15], and more recently a new travelling fire framework, based on a mobile version of Hasemi's localized fire model combined with a simple smoke layer calculation, being developed at the University of Edinburgh [17], [18]. These are briefly reviewed below.

Clifton's Travelling Fire Model

The first methodology of representing travelling fires in large compartments was put forward by Clifton in 1996 [16]. This model divides the large compartment into several design areas (named as firecells), which are then subjected to modified parametric-fire curves individually and sequentially. In the model, ventilation to firecells, pre-heating of firecells, smoke logged, and cooling after burnout are all considered. A schematic of the model is shown in Fig. 7.

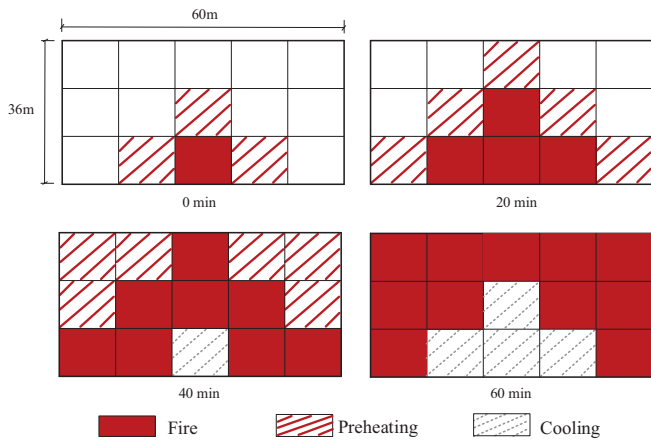


Fig. 7. Conceptual illustration of Clifton's model, adapted from [33].

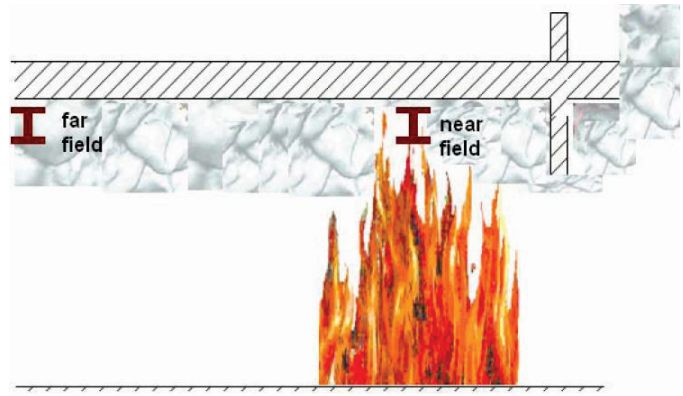


Fig. 8. Rein's near field and far field temperature schematic [2].

Although this pioneering model introduced aspects which are not considered in the conventional uniform burning assumption, it was not widely used in the fire safety engineering. Wang et al. [33] suggested reasons for the poor uptake, including lack of documentation for the procedures to implement it, and insufficient experimental validation.

Rein's Travelling Fire Model

In 2007, Rein et al. [2] put forward an alternative travelling fire methodology, based on a series of computational fluid dynamics (CFD) analyses and engineering simplifications. It proposed a near field (fire plume near the structure) and a far field (smoke) in the model, to replace the simultaneous burning assumption used in the conventional design approach (see Fig. 8). Fig. 9(a) shows a family of far field travelling fire curves that were generated by this method with different fire sizes, using a standard fire curve and a parametric fire curve (420 MJ/m² fuel load density, 25% ventilation) for comparison. The family of fires is generated by covering the full range of all possible fire sizes. It is assumed in the model that each time the fire would burn a certain surface area, A_b (m²), which is a percentage of the total floor area, A_t (m²), ranging from 1% to 100% [34].

This model was further developed by Stern-Gottfried & Rein, and eventually put forward as a design methodology in 2012 [15]. Alpert's ceiling jet correlation [35] was adopted to calculate the far field smoke temperature (see Eq. (1)), and a uniform 1200°C was assumed for the near field:

$$T - T_{\infty} = \frac{5.38}{H} \cdot \left(\frac{\dot{Q}}{r}\right)^{2/3} \quad (1)$$

where T (°C) is the peak ceiling jet temperature, T_{∞} (°C) is the ambient temperature, \dot{Q} (kW) is the heat release rate of the fire plume, H (m) is the height of the compartment ceiling, r (m) is the distance from the centre of the fire plume.

The fire size within the model is governed by the available ventilation, which is usually difficult to estimate [33], hence the user is required to parametrically assess the range of structural responses to various fire sizes. Another important feature is the local near field burning time for each fire size, which is decided by the fuel load density and the heat release rate per unit area, and for a typical office building, was suggested to be 19 min by Stern-Gottfried & Rein [15]. Moreover, the fire path of the near field is not specified in the model, as there are too many uncertainties, such as the ignition point, ventilation conditions, and fuel load distributions, which combine to preclude determination of the actual fire path in a real building [33].

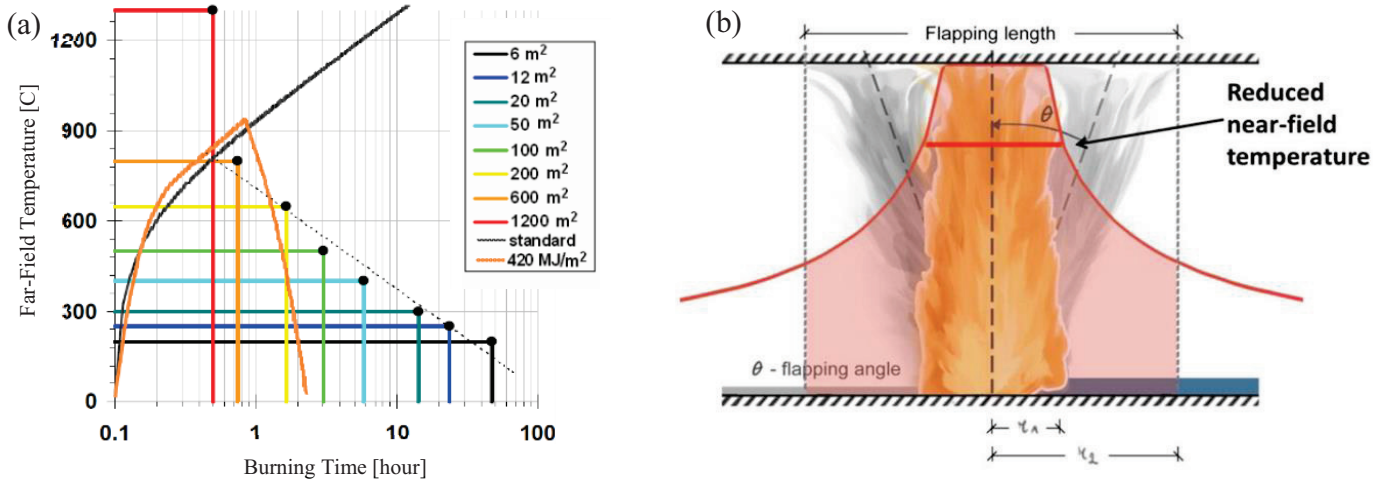


Fig. 9(a). Time-temperature curves for the far-field using Rein's model [2]; and Fig. 9(b). Flapping angle and reduced near field temperature, Rackauskaite et al. [36].

More recently, Rackauskaite et al. [36] further improved Rein's travelling fire model by taking into account more localised fire dynamics, specifically, reducing the range of possible fire sizes which should be implemented by realistically considering fire spread rates. Furthermore, the concept of flapping angle was introduced (see Fig. 9(b)), to account for the near field temperature range from 800°C to 1200°C, rather than the conservative 1200°C used in the previous version. This may lower the ceiling temperatures for some fire sizes but remains a crude approximation.

Extended Travelling Fire Method (ETFM) Framework

In the last couple of years, a new travelling fire framework has been developed and implemented by Dai et al. [17], [18]. It is based on a mobile version of Hasemi's localized fire model [37], which quantifies the local effect of a fire on adjacent structural members, and is combined with the FIRM zone model [38] for the areas of the compartment away from the fire. This combined fire model enables the analysis to capture both spatial and temporal changes of the thermal field, thus addressing more fire dynamics than Clifton's model and Rein's model. Fire temperatures are variable for the near field, contrasting the uniform 800°C-1200°C assumption in Rein's model, while all elements in one firecell share the same fire exposure history in Clifton's model. The ETFM framework also accounts for the accumulation of a hot smoke layer, variable fuel load distribution along the fire path, both of which are ignored in previous models. However, the current framework still employs a predetermined localized fire path (see Fig. 10(a) & (b)).

Hasemi's localized fire model [37], for quantifying the local effect of the travelling fire on adjacent structural members, is given by the equations below according to Eurocode 1 [39] when the fire plume is impinging the ceiling:

$$\begin{aligned} \dot{h} &= 100000 & \text{if } y \leq 0.30 \\ \dot{h} &= 136300 - 121000y & \text{if } 0.30 < y \leq 1.0 \\ \dot{h} &= 15000y^{-3.7} & \text{if } y \geq 1.0 \end{aligned} \quad (2)$$

where \dot{h} (W/m^2) is the external heat flux, y is obtained through equation $y = (r + H + z') / (L_h + H + z')$. In implementing Hasemi's localized fire model into the ETFM framework, three key parameters should be decided at each time step: fire origin, fire diameter, D (m), and heat release rate, Q (W) [17]. Fire origin is defined as the midpoint of the distance between the travelling fire burning front edge and back edge along the trajectory. The fire diameter, D (m), can be approximated as the diameter of a circular source with same burning area of the fuel. Heat release rate, Q (W), is calculated based on Eq. (3). More details of the implementation of Eq. (2) for the ETFM framework can be found in reference [17].

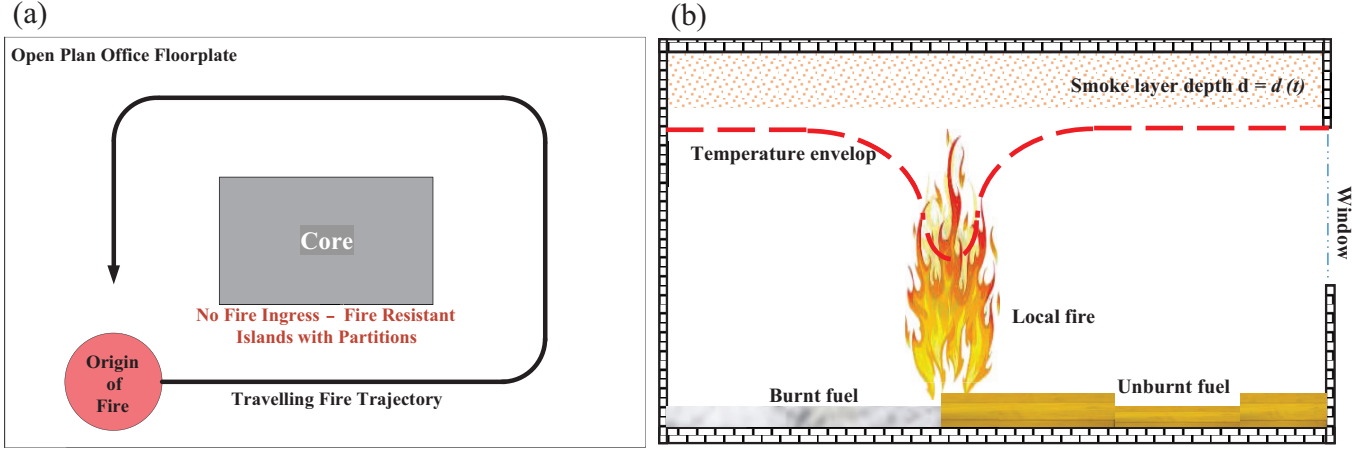


Fig. 10(a). Plan view - ETFM framework; and Fig. 10(b). Elevation view – ETFM framework, Dai et al. [17].

The assumption behind the localised fire treatment is of sufficient air being available, which is likely in many fires considering window glazing failure at 150°C - 200°C [40]. Nevertheless, the model also has the capability to represent ventilation control, which is provided by the FIRM zone model. This framework also includes non-uniform burning rates of the travelling fire along the trajectory; changing fuel load density; and variable heat release rates. The speed of the travelling fire is decomposed into two variables: the constant fire spread rate, which determines the front edge location of the travelling fire; and the burn-out time, which determines the back edge location of the travelling fire. Moreover, a concept of regulatory minimum fuel depth (RMFD), uniformly distributed over the entire floor plate, is introduced in the model. It corresponds to a reference travelling fire spread rate and a certain level of fuel load density, based on experimental observations and design guides such as Eurocode 1 [39], respectively.

The two most important parameters in this travelling fire framework are travelling fire speed (as mentioned above) and total heat release rate [17]. The heat release rate, Q (W), is defined under the assumption that fire is at the steady state, given by:

$$Q = 1000 \cdot RHR_f \cdot A_{fi} \quad (3)$$

where RHR_f (kW/m^2) is the maximum heat release rate per unit area in fuel controlled conditions, which can be referred to Eurocode 1 [39] for different occupancies, and A_{fi} (m^2) is the burning area of the fuel.

To reproduce pre-heating and post-heating effects, the combination of energy conservation and smoke generation is brought into the travelling fire framework in an elementary way, considering a varying distribution of fuel along the trajectory [17]. The depth of the smoke layer is assumed to be time dependent and uniform over the whole ceiling (see Fig. 10(b)). Smoke is considered to accumulate as more lumped fuel is consumed locally and the rate of air entrainment can be determined using a number of different models. For example, the Thomas model [41], which is an empirical equation to estimate the mass rate of production of hot gases, M_f (kg/s), is given by:

$$M_f = 0.188 \cdot W_{fi} \cdot (Y)^{3/2} \quad (4)$$

where W_{fi} (m) is the perimeter of the fire, Y (m) is the height of the zone free of smoke.

The average temperature of the hot smoke layer, θ_c (°C), is calculated by using FIRM zone model [38], which accounts for energy conservation, mass conservation, ventilations with vertical openings, and heat losses through compartment boundaries, etc.

In addition, a flashover scenario is permitted in this framework, and the fire transitioning from a localised travelling fire to a whole compartment fire when a defined threshold is met, e.g. the temperature of the hot smoke layer reaches 500°C.

A potential limitation of the ETFM framework is the applicability of Hasemi's localized fire model, which is only strictly valid for fire diameters is less than 10m, and the rate of heat release less than 50 MW [39], though these are quite large fire sizes. Another limitation of the ETFM framework is from the simplicity of the representation of ventilation, as in reality this may play a very important role, e.g. changing the fire travelling trajectory, heat release rate, etc.

Summary of the Analytical Models

Table 2 summaries the above analytical models by categorizing with different model features, such as the heat release rate consideration, fire size determination, and fire path type, etc. Clifton's model, as the earliest version of travelling fire analytical model, is actually a way of applying modified parametric fire curves for series of firecells with a time lag. The fire science knowledge it involved is mainly from the utilization of these fire curves, where the fuel load density, compartment boundary conditions, and ventilations are considered. Rein's travelling fire model contains more fire dynamics, such as the considerations of heat release rate (HRR), mass conservation, and flapping angles, etc. ETFM framework can be regarded as an improvement of Rein's model, as similar assumptions are made based on Rein's work. For example, the determination of fire size, HRR, spread rate are the same in both models.

Table 2. Summaries of the travelling fire analytical models.

Models Categories	Clifton's Travelling Fire Model, [16] [33]	Rein's Travelling Fire Model, [2] [15] [36]	ETFM Framework, [17], [18]
Near field temperature	Time-temperature curve for firecells	800°C -1200°C, flapping angle	Localised fire model
Far field temperature (i.e. smoke)		Alpert's ceiling jet model	Simple zone model (e.g. FIRM)
Smoke accumulation	No	No	Yes
Fire path	Firecell to neighboured ones	Not defined	Predefined trajectory
Spread rate	From observation [36]	From observation [36]	From observation [36]
Non-uniform fuel	No	No	Yes
Fire size	Decided by fuel load density	Decided by fuel & fire spread	Decided by fuel & fire spread
HRR consideration	No	Yes	Yes
Mass conservation	No	Yes	Yes
Energy conservation	No	No	Yes
Compartment boundary	Yes	No	Yes
Ventilation/fuel controlled	Ventilation controlled	Fuel controlled	Fuel & ventilation controlled

Generally, the development of these analytical models is based on simple theoretical assumptions and experimental observations. The role of experiments in the analytical development is providing sufficiently general data and characterising likely worst credible conditions, to facilitate researchers in developing and validating their models, although in reality large uncertainties will remain. However, it is worth noting that travelling fire models generally don't consider the conditions in which a travelling fire may develop. They are implemented in the analysis by forcing the development of a fire moving across the floor area. Therefore, more experiments are needed to characterise these conditions in more generalised scenarios.

CASE STUDY USING THE ETFM FRAMEWORK

Clifton's travelling fire model [16][23] and Rein's travelling fire model [2][10][11][15][34][36][42] have been explored by researchers around the world on both thermal and structural response for the past two decades. This section shows the latest development of ETFM framework and its implementation. Further, it emphasizes the fundamental need of new travelling fire experiments to be carried out, for improving the understanding of the travelling fire behaviour and its relevant theoretical methodologies.

Fig. 11(a) shows the plan view of an idealised structural layout for case study (630m² floor area), which is generic in modern tall buildings with a core (162m² area) in the middle. The clear floor height is 3.85m. The total vent widths of this large compartment are 28m. The soffit height and sill height are 3m and 1m respectively. The investigated beam size is UB 305×127×42 located at the top right of the floor plan. The ignition line of the travelling fire is also shown as in Fig. 11(a). The travelling fire path is predefined to be under the mid-span of the main beams, which would normally represent the worst case for the structural response (see Fig. 10(a)). A 'base line scenario' of the travelling fires is assumed with fuel load density ($q_{f,k}$) 570 MJ/m², heat release rate per unit area (RHR_f) 500 kW/m², and fire spread rate (v) 10 mm/s. Different fire scenarios would be generated with changing v or $q_{f,k}$, (1.6-15 mm/s [36], 100-780 MJ/m² [39]) but keeping the other two values as constants from the 'base line scenario'.

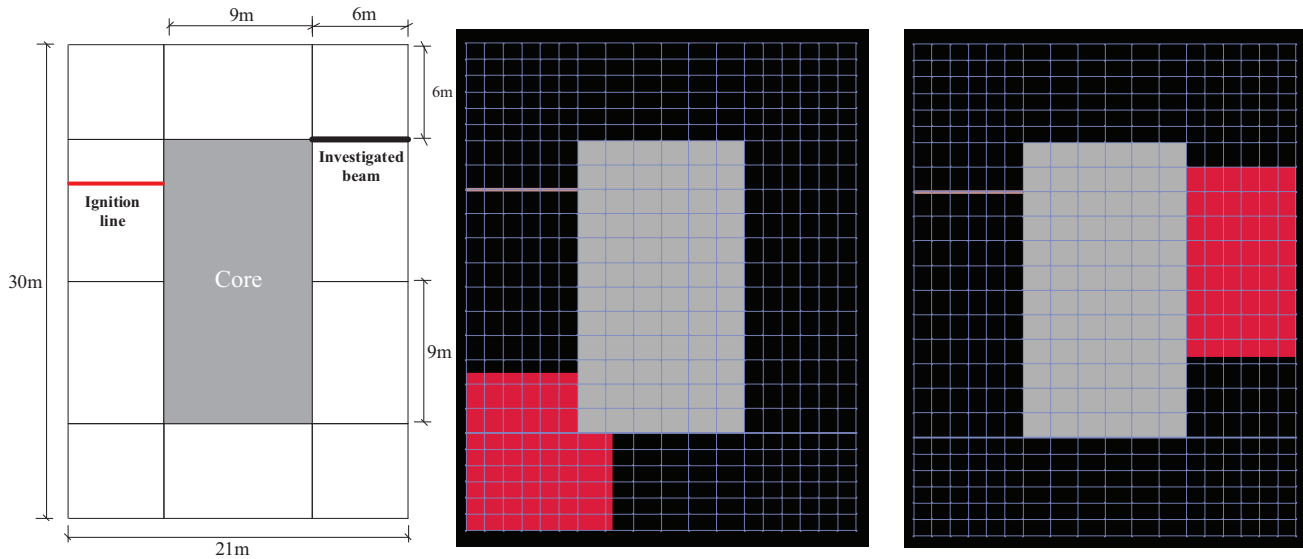


Fig. 11(a). Case study plan view; Fig. 11(b), Fig. 11(c) SIFBuilder visualization during heat transfer analysis at 38 min, 87min respectively at the 'base line scenario' of the travelling fires: $q_{f,k} = 570$ MJ/m², $RHR_f = 500$ kW/m², $v = 10$ mm/s.

The newly developed travelling fire modules in SIFBuilder [18] are used to perform both the fire and heat transfer analysis. SIFBuilder is an OpenSees-based software framework [19], with features of facilitating fire model, heat transfer, and thermo-mechanical analysis for large structures in one software package. Heat transfer results of the investigated steel member using mobile Hasemi's fire model, and the FIRM zone model are illustrated separately as below. Moreover, the evolutions of smoke temperature and smoke depth are also included. Fig. 11(b) and (c) are the two screenshots during the fire model analysis in SIFBuilder, showing two different fire locations at two specific time points.

Three sides of the investigated beam are exposed to the thermal impact of the mobile Hasemi's fire model /FIRM zone model, since a concrete slab is assumed to be at the top. Two dimensional heat transfer analysis is carried out for the cross-section at the mid-span of the beam, using 35W/m² K as the convection coefficient for fire-exposed surfaces and 0.7 as the emissivity of the steel (two coefficients recommended in [39]).

In Fig. 12(a), apart from the longer fire duration generated when the smaller fire spread rate v is used, the travelling fire scenarios with spread rates from 5 mm/s to 15 mm/s produce similar thermal impact in terms of the maximum steel temperatures. However, the two 'slow' fires with spread rates 1.6 mm/s and 2 mm/s produce relatively lower steel temperatures. The reason is because the fire HRR is calculated based on fire area (see Eq. (3)), and fire area is a resultant of fire spread rate and burning rate of the fuel. Hence, although 'slow' fires have more time to heat up the steel member, they produce lower thermal impact due to smaller

fire areas and HRR generated. Fig. 12(b) illustrates that longer fire durations and higher thermal impact are generated if higher fuel load densities are used.

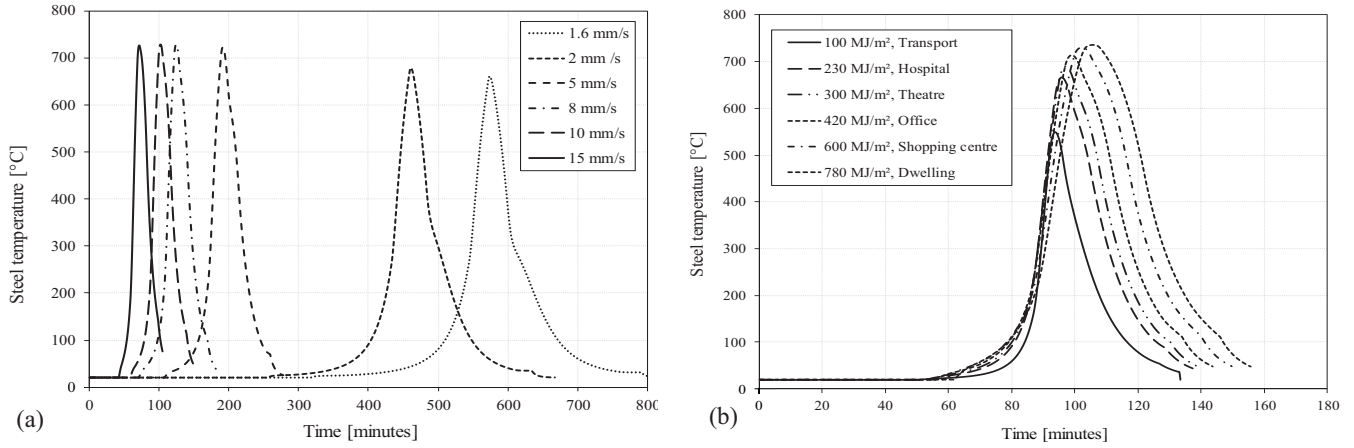


Fig. 12(a). Heat transfer results from mobile Hasemi's fire model contribution, with various spread rates ranging from $v = 1.6$ mm/s to $v = 15$ mm/s; and Fig. 12(b). with various fuel load densities range from $q_{f,k} = 100$ MJ/m² to $q_{f,k} = 780$ MJ/m².

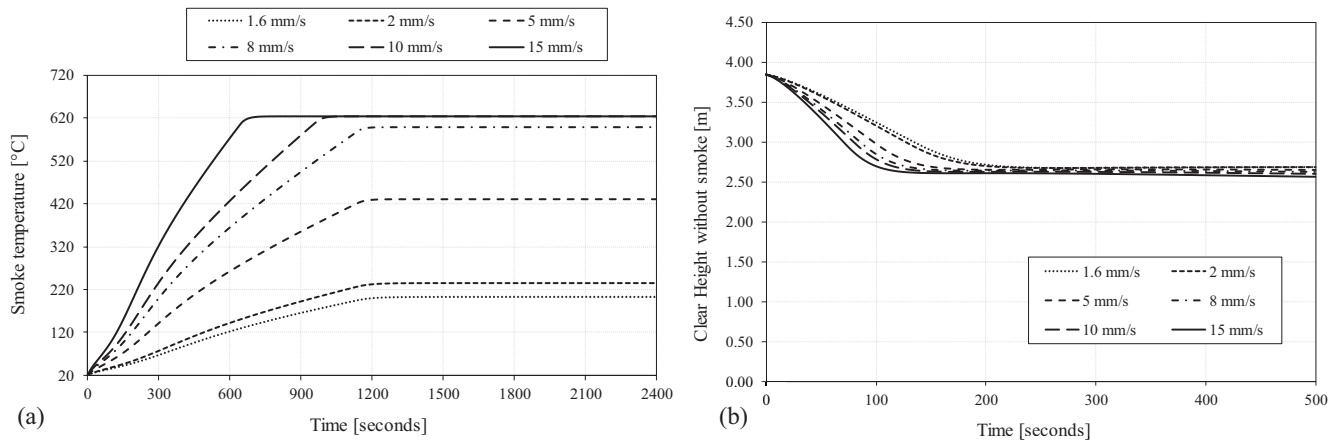


Fig. 13(a). Smoke temperature evolution; and Fig. 13(b). Height of zone free of smoke, with various spread rates range from $v = 1.6$ mm/s to $v = 15$ mm/s.

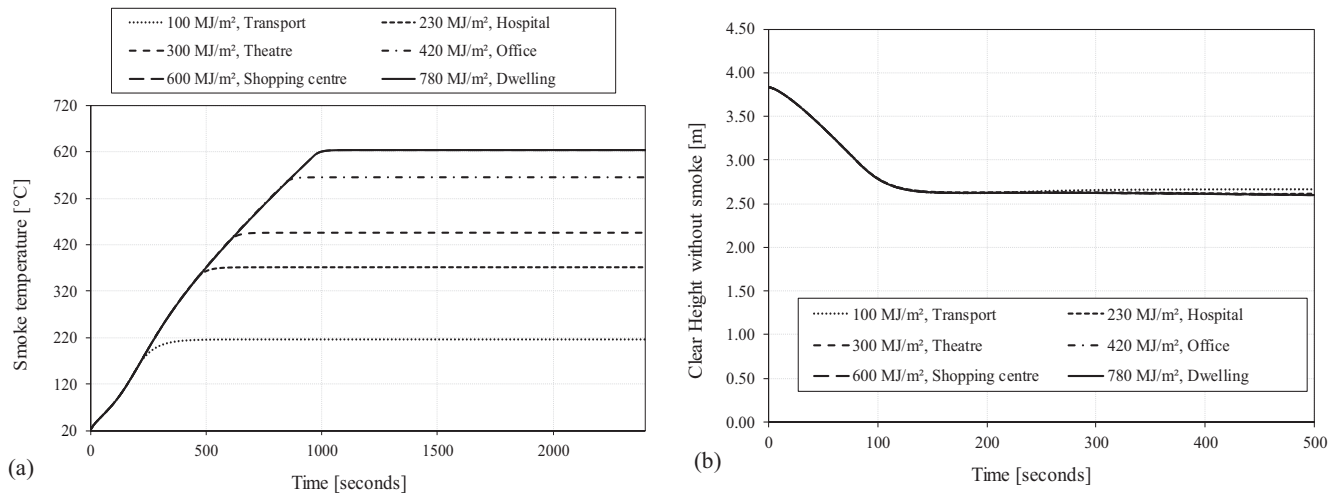


Fig. 14(a). Smoke temperature evolution and Fig. 14(b). Height of zone free of smoke, with various fuel load densities range from $q_{f,k} = 100$ MJ/m² to $q_{f,k} = 780$ MJ/m².

Fig. 13(a) demonstrates that the travelling fire scenarios with higher fire spread rates (e.g. 10 mm/s, 15mm/s) generate higher smoke layer temperature, with quicker temperature increase rate. The reason is because the energy conservation equation, from the FIRM zone model for calculating the transient smoke layer

temperature increase, is directly dependent on the HRR, which decides the amount of energy to be ‘pumped’ into the smoke layer at each time step. The same as discussed earlier, the HRR is calculated based on fire area, and fire area is a resultant of fire spread rate and burning rate of the fuel. Therefore, ‘fast’ fires produce higher thermal impact due to bigger fire areas and HRR generated. Fig. 13(b) illustrates that the smoke layer can become steady within 200 s for all the travelling fire scenarios. Fig. 14(a) shows that the travelling fire scenarios with higher fuel load densities generate higher smoke layer temperatures. Again, it is directly dependent on the HRR which decides the amount of energy to be ‘pumped’ into the smoke layer at each time step, thus depending on the spread rate and burning rate. Larger fuel load densities would generate slower fire burning edge, thus a larger fire area would be produced. Therefore, ‘dense’ fires produce higher thermal impact due to bigger fire areas and HRR generated. Fig. 14(b) shows the smoke depth evolution, which is nearly independent of fuel load densities in the initial spread phase of the fire. Fig. 15(a) and 15(b) are the steel temperatures via heat transfer analysis in SIFBuilder.

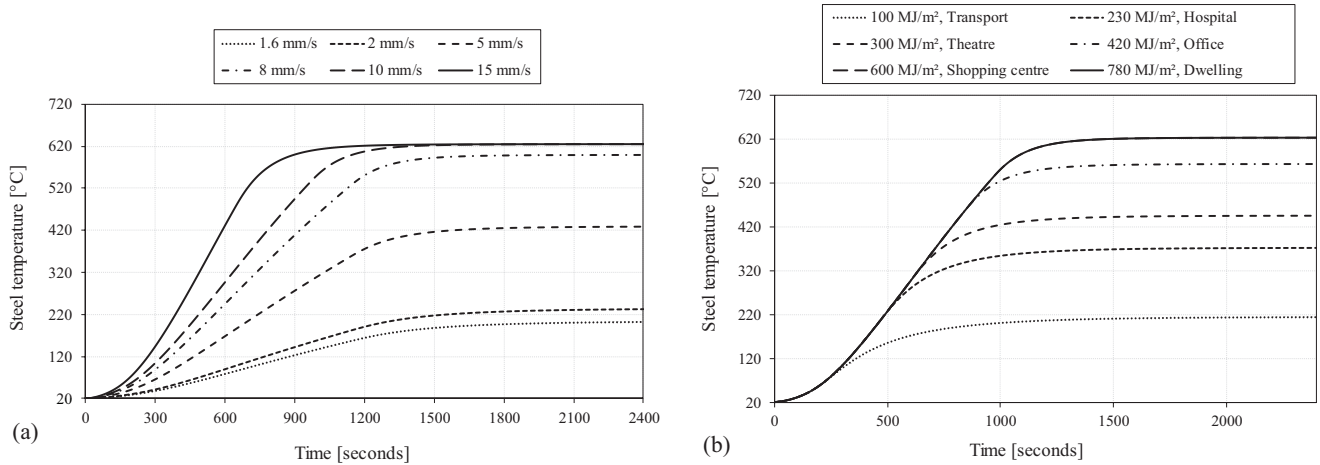


Fig. 15(a). Heat transfer results from FIRM zone model contribution, with various spread rates ranging from $v = 1.6$ mm/s to $v = 15$ mm/s; and Fig. 15(b). with various fuel load densities range from $q_{f,k} = 100$ MJ/m² to $q_{f,k} = 780$ MJ/m².

Table 3 below presents the sensitivity of the results to selected design parameters relevant to performance-based structural fire design.

Table 3. Summaries of the travelling fire thermal impact due to v , and $q_{f,k}$.

$v, q_{f,k}$ Thermal impact	Low fire spread Rate	High fire spread Rate	Low fuel load density	High fuel load density
Steel temperature from moving Hasemi's model	Slightly lower	Slightly higher	Lower	Higher
Thermal impact duration from moving Hasemi's model	Slightly longer	Slightly shorter	Shorter	Longer
Steel temperature from FIRM zone model	Much lower	Much higher	Much lower	Much higher
Smoke layer temperature from FIRM zone model	Much lower	Much higher	Much lower	Much higher
Time to form a steady smoke layer	Slightly slower	Slightly quicker	Not sensitive	
Smoke layer depth	Slightly thinner	Slightly thicker	Not sensitive	

Although these results are based on a single assumed scenario, they do provide some insights into how the key variables such as travelling fire spread rate and fuel load densities might affect the structural thermal response. In the ETFM framework, these two variables are the essential inputs for the determination of HRR [17] and given the uncertainty in their values it is important to characterise the sensitivity of the structural response to their assumed values. Moreover, as discussed in the previous section (see Table 1), there is no

single experiment which possesses both HRR data and structural response data. Therefore, new travelling fire experiments are also required with both structural and fire key variables recorded to further develop and validate the theoretical framework.

CONCLUSIONS

This paper has examined experiments conducted for characterizing travelling fires, in conjunction with review of the current analytical travelling fire models, including the recent development of the ETFM framework by the authors. A case study of the ETFM framework is presented and used to explore the sensitivity of uncertainties in key input parameters (fire spread rate and fuel load density) on the predicted outputs. It is apparent that travelling fire research is still at an early phase of development, and the main limitation to progress is the lack of detailed measurements of required parameters in realistic large-scale tests. Design of appropriate tests can be effectively informed by modelling studies such as those reported here, and requires close collaboration between structural and fire engineers' teams. Their value will be in providing better insights into fire behaviour in realistic travelling fire scenarios, which will ultimately provide a robust methodology for performance-based structural fire engineering.

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